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Improvements to Passive Acoustic Tracking Methods for Marine Mammal Monitoring

Eva-Marie Nosal
Department of Ocean and Resources Engineering
University of Hawaii at Manoa
2540 Dole Street
Holmes Hall 405
Honolulu, HI 96822, USA
phone: (808) 956-7686 fax: (808) 956-3498 email: nosal@hawaii.edu

Award Number: N000141210206
http://www.soest.hawaii.edu/ore/faculty/nosal

LONG-TERM GOALS

The long-term goal of this project is to improve model-based passive acoustic methods for tracking marine mammals. When possible, tracking results are used to study marine mammal behavior and bioacoustics.

OBJECTIVES

The first three objectives of this project are to investigate and implement several specific ideas that have the potential to improve the accuracy, efficiency, and applicability of model-based passive acoustic tracking methods for marine mammals:

1) Invert for sound speed profiles, hydrophone position and hydrophone timing offset in addition to animal position.
2) Improve maximization schemes used in model-based tracking.
3) Use information in addition to arrival times for tracking.

The final objective of this project is to:

4) Improve and test approaches to simultaneously track multiple animals simultaneously in cases where it is difficult/impossible to separate and associate calls from individual animals.

APPROACH

Eva-Marie Nosal is the key individual participating in this work as the principal investigator and main researcher.

This project uses existing datasets. The main effort is directed toward data collected at Navy Ranges, with data from PMRF provided by S. Martin and data from AUTEC provided by D. Moretti. Other datasets that use bottom-mounted sensors are also be considered if available and appropriate. The main

species of interest in these datasets are sperm whales, beaked whales, minke whales, and humpback whales. Most methods developed will be generalizable to other species.

This project uses model-based tracking methods [e.g. Tiemann et al. 2004; Thode 2005; Nosal 2007] that have been developed to localize animals in situations where straight-line propagation assumptions made by conventional marine mammal tracking methods fail or result in unacceptably large errors. In the model-based approach, a source is localized by finding the position that gives predicted arrival times that best match the measured arrival times. This is done by creating a likelihood surface that gives the probability of an animal at any position in space. The maxima of this surface give the estimated animal position(s). Arrival time predictions are made using a sound propagation model, which in turn uses information about the environment including sound speed profiles and bathymetry. Calculations are based on measured time-of-arrivals (TOAs) or time-differences-of-arrival (TDOAs), modeled TOAs/TODAs, estimated uncertainties, and any available a priori information. All methods are fully automated through MATLAB code.

The approaches taken for each of the objectives are further expanded separately below:

Objective 1: <u>Invert for sound speed profiles, hydrophone position and hydrophone timing offset in addition to animal position</u>
Almost all marine mammal tracking methods treat animal position as the only unknown model parameter. Other parameters (sound speed, hydrophone position, hydrophone timing) are treated as known inputs and estimated error in these “knowns” is propagated to give error in estimated animal position. This is not always the best approach since it can cause location errors to become unnecessarily large. Moreover, small offsets in hydrophone timing lead to entirely incorrect position estimates (and unfortunately timing is a serious practical problem for passive acoustic tracking systems that comes up repeatedly in real-world datasets). Moreover, there are situations in which sound speeds, phone position and/or timing offsets are entirely unknown.

Sound speed, phone position and/or timing offsets can be readily be included in the set of unknown model parameters in model-based tracking, with any known information incorporated as *a priori* information. This approach has potential to yield much improved position estimates and/or to give position estimates in cases that would be otherwise impossible. This approach has been used successfully by the underwater acoustics community [e.g. Collins and Kuperman, 1991; Fialkowski et al. 1997; Tollefsen and Dosso, 2009] but modifications for and application to marine mammal tracking remains limited [but see Thode 2000].

Objective 2: <u>Improve maximization schemes used in model-based tracking</u>
In past model-based localization work, likelihood surface maximization has usually been implemented using a grid search (sometimes using multiple-step approach starting with coarse grids that are successively refined). This part of the project investigates the benefit of implementing more sophisticated maximization schemes to find local maxima in the likelihood surfaces. Potential benefits of using these schemes include reduced run times and more precise position estimates. In addition, one serious drawback of the approach from Objective 1 (increased parameter space) is increased computational complexity due to larger search spaces; using more sophisticated maximization schemes is critical in keeping the problem computationally viable.

Objective 3: Use information in addition to arrival times for tracking
Almost all marine mammal tracking methods rely solely on arrival times. There is often additional information that changes with animal position and can consequently be used to obtain/improve position estimates. Several researchers have used sound pressure level or propagation characteristics for tracking [e.g. Cato 1998; McDonald and Fox 1999; McDonald and Moore 2002; Wiggins et al. 2004]. Past approaches have generally been limited to assumptions of omni-directional sources and spherical spreading; assumptions that do not always apply. With some modification, the model-based localization methods used in this project can incorporate source levels and transmission loss and account for confounding factors such as source directionality (e.g. by including animal orientation and beam pattern in the inversion process). These modifications will be made to investigate the feasibility of incorporating received levels in tracking methods.

Objective 4: Multiple animal tracking
One approach taken to track multiple animals involves developing source separation methods that are applied prior to tracking. Once sources have been separated on each hydrophone, the association problem (identifying the same call on all hydrophones) is greatly simplified. If multiple animals can thus be separated and calls associated, the problem is reduced to multiple applications of single-animal tracking methods.

Different approaches for multiple animal tracking are being explored for cases in which source separation/association is not possible. One possibility is to use the model-based tracking framework and include all possible associations (or cross-correlation peaks) in the likelihood surfaces. This approach requires the maximization method from Objective 2.

WORK COMPLETED

During FY15, the multiple animal time-of-arrival localization (MTOA) method developed in prior years [Nosal 2013] was extended to make use of higher order (e.g. multipath) arrivals. To accomplish this, the set of hydrophone used for localization is augmented with virtual hydrophones that correspond to the expected higher-order arrivals.

Also in FY15, a source level localization method (henceforth referred to as the "received level method", RL) was developed that includes source sound pressure level as an unknown parameter. This differs from the source level localization method developed in FY13 (henceforth referred to as the "received level difference method", RLD) in that it solves for source level directly rather than using differences in received source levels between hydrophone pairs. Doing this is analogous to using time of arrivals (TOAs) and solving for sound emission time instead of using time-differences of arrival (TDOA) [see Nosal 2013 for a detailed discussion of this difference].

Finally, the MTOA and RL methods were combined to produce a method (MTOA+RL) that uses both arrival times and received levels to estimate source locations. The unknown parameters that are inverted for include source emission times, source levels, and animal positions. Because of the large parameter space involved, implementation relies heavily on the improved maximization schemes from FY12 and FY14.

RESULTS

The advantages of including higher order arrivals when estimating animal location are well known. Most importantly, position estimates are improved and fewer hydrophones are required to localize. The MTOA method using higher-order arrivals capitalizes on these advantages without requiring arrivals to be classified (as direct, surface-reflected, etc) or associated between hydrophones. This has potential to help realize the goal of fully-automated localization in unfamiliar datasets (although in the current formulation, the number of expected arrivals must still be known or estimated *a-priori* – a requirement that can be relaxed through further development). To validate the MTOA method, it was applied to several datasets that have been well explored by the PI. Application to the case of a single sperm whale on 5 AUTEC hydrophones with well-defined surface reflections was straightforward and gave position estimates that were nearly as good as a method [from Nosal and Frazer 2007] that carefully classified and associated each click arrival [Figure 1]. A second application to a case with multiple animals gave position estimates that had smaller errors and smoother paths than using direct arrivals only.

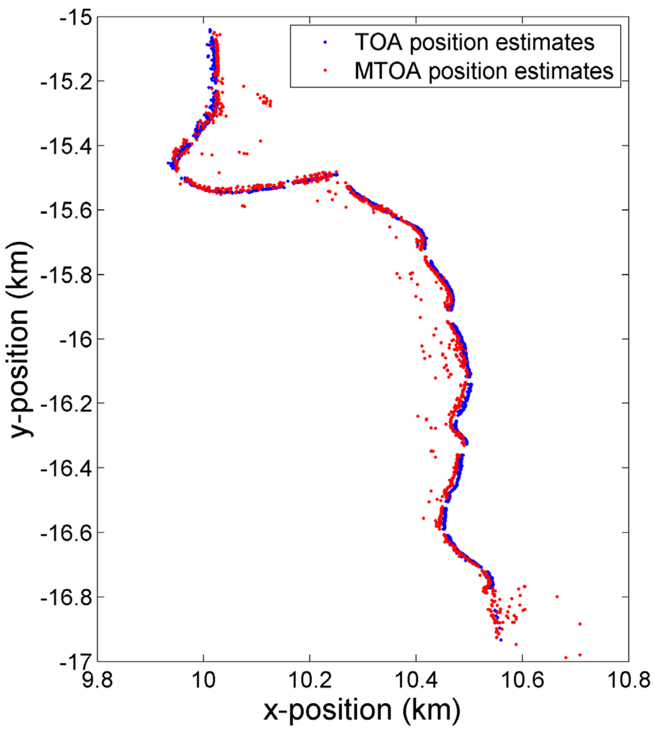

Figure 1. Comparison of position estimates from a TOA method that classifies and associates clicks and surface reflections prior to localization [from Nosal and Frazer 2007] and the MTOA method with higher-order arrivals developed here. The MTOA method assumed two arrivals: direct and surface-reflected. Position estimates from the MTOA method are similar to those from the TOA method but didn't require an association and classification step.
Data are from the well-known DCLDE 2015 localization dataset: a sperm whale recorded on 5 bottom-mounted hydrophone at AUTEC.

The most impactful advantage of using RL instead of RLD is that source level is treated as an unknown parameter, which allows error in source level to be absorbed in the resulting source level estimate. In the RLD method, on the other hand, estimated source position must account for the error associated with omni-directional source assumptions in the (ubiquitous) reality of directional sources. This produces unnecessarily large source position uncertainties which can be reduced via the RL method. The improvement is especially important for localization of moderately directional sources (neither of the methods are applicable for highly directional sources).

The MTOA+RL method was applied to a dolphin click sequence from a single hydrophone dataset. Using arrival times only gave unreliable position estimates, primarily because there wasn't enough information in arrival alone and because arrival times had too much uncertainty to clearly resolve source positions. Including received levels was needed to produce reasonable location (range and depth) estimates [Figure 2, Nosal DCLDE].

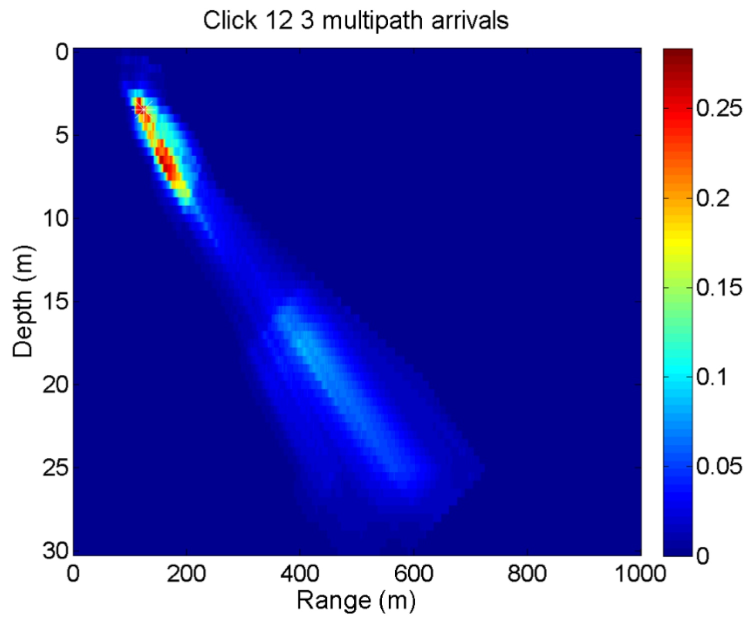

Figure 2. MTOA+RL ambiguity surface (red represents higher probability of source location) using the direct arrival and 3 multipath arrivals for a dolphin click recorded on a single seafloor-mounted hydrophone. The hydrophone [described in Fedenczuk et al. 2015] was tethered 5 meters off the seafloor in 30 m water depth.

IMPACT/APPLICATIONS

The localization and tracking methods developed in this project are useful for monitoring and studying marine mammal bioacoustics and behavior in the wild. Tracking results can be used to establish detection ranges and calling rates that are critical in density estimation applications. Methods developed to track marine mammals are useful for sources other than marine mammals (e.g. tracking of surface vessels can help to monitor fishing efforts in marine protected areas).

RELATED PROJECTS

NSF award 1017775. Signal Processing Methods for Passive Acoustic Monitoring of Marine Mammals. (PI: E-M Nosal, Co PI: A Host-Madsen). Application of signal processing methods from speech and communications to passive acoustic monitoring of marine mammals. Focuses on detection and classification instead of on localization (this project). Progress made in this project directly benefits the proposed project (and vice versa).

ONR (Ocean Acoustics) N000141010334. Acoustic Seaglider: Philippine Sea Experiment (PI: B Howe, CoPI: E-M Nosal, G Carter, L VanUffelen). Use of gliders to record transmissions in the PhilSea10 tomography experiment. Some of the inverse methods used share similar theory and implementation. In the PhilSea project, the “unknown” of interest is sound speed (hence temperature and salinity) while in this project it is source location.

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